WEED SCIENCE

Cotton Yield Loss Potential in Response to Length of Palmer Amaranth (*Amaranthus palmeri*) Interference

A. W. MacRae, T. M. Webster*, L. M. Sosnoskie, A. S. Culpepper, and J. M. Kichler

ABSTRACT

Field studies were conducted near Ideal, GA in 2006 and 2007 to determine the influence of simulated delayed emergence of Palmer amaranth at several densities on cotton yield and weed growth. Palmer amaranth plants in the 6- to 8-leaf stage were transplanted at five densities (ranging from 0 to 10 plants per 6.1 m row⁻¹) and four time intervals defined by cotton leaf stage (3-, 8-, 12-, and 17-leaf cotton). Prior to harvest, Palmer amaranth biomass was removed from the plots and quantified, Palmer amaranth seed production measured, and cotton yield determined. When Palmer amaranth plants were transplanted in 3- or 8-leaf cotton, cotton yield was reduced approximately 6% for every Palmer amaranth per 6.1 m of row, with a maximum cotton yield loss of 60%. In contrast, there was no effect of Palmer amaranth density on cotton yield when Palmer amaranth established at the 12- and 17-leaf stages of cotton. Maximum Palmer amaranth biomass, averaged over all densities, was achieved when Palmer amaranth was established at the 3- and 8-leaf stages of cotton (9,190 kg ha⁻¹), while Palmer amaranth biomass from plants established at the 12- and 17-leaf stages of cotton was reduced 73%. Palmer amaranth seed production per plant ranged from 61,000 when transplanted at the 3-leaf cotton stage to 14,000 seeds per plant for Palmer amaranth transplanted at the 17-leaf cotton stage. To avert cotton yield loss, Palmer amaranth interference should be eliminated prior to the 12-leaf stage of cotton; later-emerging plants may not affect cotton yields, but will replenish the soil seedbank.

A.W. MacRae, L.M. Sosnoskie, and A.S. Culpepper, Dept. of Crop and Soil Sciences University of Georgia, P.O. Box 1209, Tifton, GA 31794-1209; T.M. Webster*, Crop Protection and Management Research Unit, USDA-ARS, P.O. Box 748, Tifton, GA 31794-0748; and J.M. Kichler, Macon County Extension Service, University of Georgia, Oglethorpe, GA 31068
*Corresponding author: Ted.Webster@ars.usda.gov

With the introduction of glyphosate-resistant cotton, many growers eliminated the use of soil-applied residual herbicides and cultivation and, instead, relied heavily on glyphosate to control weeds (Culpepper et al., 2010). In 2004, Palmer amaranth (*Amaranthus palmeri* S. Wats.) with resistance to glyphosate was confirmed in Georgia at a field site where cotton was grown continuously and glyphosate was the only herbicide used (Culpepper et al., 2006). The mechanism of glyphosate resistance in Palmer amaranth at this site was over-amplification of the EPSPS (5-enolpyruvlshikimate-3-phosphate synthase) gene, a unique form of herbicide resistance (Gaines et al., 2010). Although glyphosate resistance can be transferred through pollen (Sosnoskie et al., 2012), it is not clear if this is the primary mechanism of spread in Georgia. Glyphosate-resistant (GR)-Palmer amaranth has now been detected in multiple states in the southern US (Culpepper et al., 2008; Nichols et al., 2009; Steckel et al., 2008). As of 2012, GR-Palmer amaranth populations have been confirmed in at least 16 US states (Heap 2012). Palmer amaranth with resistance to other herbicide mechanisms of action have been documented, including several cases of multiple resistance (Heap 2012).

Palmer amaranth is a competitive weed species due, in part, to its season-long germination phenology and its high rate of photosynthesis relative to other C4 plants, which enhances its ability as a crop competitor (Ehleringer, 1983; Gibson 1998; Steckel, 2007). Palmer amaranth rapidly germinated at 30°C, with complete germination on the first day, similar to smooth pigweed (*Amaranthus hybridus* L.) (Steckel et al., 2004). In contrast, six other *Amaranthus* spp. had much slower rates of germination, taking between three and eight days to achieve 50% germination (Steckel et al., 2004). Palmer amaranth readily grew taller than related *Amaranthus* spp. (Horak and Loughin, 2000) and has been observed to increase in plant height 5 cm in a single day (Culpepper et al., 2010; Horak and Loughin, 2000). Palmer amaranth produces numerous roots that are capable of penetrating soil layers to obtain additional soil resources, likely providing another competitive advantage over other

competing species, including crops (Guo and Al-Khatib, 2003; Place et al., 2008; Wright et al., 1999).

Palmer amaranth interference can significantly reduce the yield of most agronomic crops. Previous studies demonstrated maximum potential crop yield losses due to full season Palmer amaranth interference of 54% (1.1 Palmer amaranth plants m^{-1}) for cotton (Morgan et al., 2001); 79% (8 Palmer amaranth plants m^{-1}) for soybean (*Glycine max*) (Bensch et al., 2003); 91% (8 Palmer amaranth plants m^{-1}) for corn (*Zea mays*) (Massinga et al., 2001); 63% (13.7 Palmer amaranth plants m^{-2}) for grain sorghum (*Sorghum bicolor* ssp. *bicolor*) (Moore et al., 2004); and 68% (5.5 Palmer amaranth plants m^{-1}) for peanut (*Arachis hypogaea*) (Burke et al., 2007). Field studies conducted in Oklahoma determined that cotton yield losses were 3 and 77% when Palmer amaranth interference ceased at 21 and 63 days after emergence, respectively (Fast et al., 2009).

Currently the only options for glyphosate-resistant (GR)-Palmer amaranth control in glyphosate-resistant cotton systems are herbicides applied prior to Palmer amaranth emergence. In Georgia the sequential use of pendimethalin plus fomesafen PRE, metolachlor POST, and diuron plus MSMA at layby are recommended for the management of Palmer amaranth (Culpepper and Kichler, 2009). Individually, none of these herbicides will control GR-Palmer amaranth for the entire season. Efficacy and dissipation rate of these herbicides are regulated by numerous environmental factors that can lead to variable weed control at any stage during cotton production. Therefore, studies were initiated in Georgia to evaluate the influence varying lengths of interference between Palmer amaranth and cotton on crop yield, weed growth, and weed seed production.

MATERIALS AND METHODS

Field studies were conducted near Ideal, GA in 2006 and 2007 in an area with a history of continuous cotton and a naturalized population of GR-Palmer amaranth. Cotton (Deltapine 'DP-555' B/RR) was planted 15 May 2006 and 17 April 2007 in rows spaced 91 cm apart at a population density of 9.8 seeds m^{-1} of row. Planting time was dictated by rainfall patterns, as this study was conducted on a farm that did not have supplemental irrigation. A broadcast application of pendimethalin (1.4 kg ai ha^{-1}) was applied PRE to control undesired weed species. In the absence of overhead irrigation at this field site, we were unable

to ensure continual Palmer amaranth emergence at the appropriate timing and location with each plot. Therefore, Palmer amaranth plants (six to eight-leaf stage) were transplanted in the cotton row at densities of 0, 2, 3, 5, and 10 plants per 6.1 m of row from adjacent areas within the field. These densities were established at four biweekly time intervals defined by cotton leaf stage (3-, 8-, 12, and 17-leaf stage cotton) and Palmer amaranth emergence. These timings were selected to approximate the competitive effects of Palmer amaranth weed escapes from a PRE herbicide (3-leaf cotton stage), early and late POST herbicides (8- and 12-leaf cotton stages, respectively), and layby herbicide (17-leaf stage cotton). The area of newly emerged Palmer amaranth plants was treated with glyphosate (0.87 kg ae ha^{-1}) POST at 10 to 12 days prior to transplanting to ensure that only GR-Palmer amaranth were used in the study. The soil around each seedling Palmer amaranth plant (8 cm radius) was excavated with minimal root disturbance, brought to adjacent plots in the same field, and transplanted into appropriate positions and densities in the treatments. Transplanted Palmer amaranth plants were then watered to minimize transplant shock. Desired weed densities were maintained through hand-weeding. At the conclusion of the growing season, Palmer amaranth seeds per plant were measured, Palmer amaranth plant biomass was measured and seed cotton yield determined. Palmer amaranth seed was manually threshed and weighed; a subsample was weighed and counted to quantify seed production for each plant.

Cotton yield loss, Palmer amaranth biomass, and seed production data were subjected to mixed models analysis of variance (MMANOVA) (SAS, 2003). Data were transformed prior to analysis to improve normality and homogeneity of variance. Cotton leaf stage and Palmer amaranth density were included as fixed effects in the model; year and the year by replication interaction were included as random effects. Contrasts and regression analysis were used to further describe the data when MMANOVA indicated a significant effect of a main factor.

RESULTS AND DISCUSSION

Cotton yield. Data for the early (3- and 8-leaf stages of cotton) Palmer amaranth transplant timings were combined due to a statistical similarity in cotton yield response as determined using MMANOVA. Similarly, late (12- and 17-leaf stage cotton) Palmer amaranth establishment timings were also combined.

There was a linear relationship between cotton yield loss and Palmer amaranth density when weeds were transplanted at the 3- and 8-leaf cotton stages, and competed with the cotton for 121 to 125 days and 107 to 115 days when transplanted at the 3- and 8-leaf cotton stages, respectively (Figure 1). Cotton yield loss increased approximately 6% for every Palmer amaranth per 6.1 m of row at the early transplant timings, with a maximum cotton yield loss of 60% (10 plants per 6.1 m of row). In Texas, full-season interference from Palmer amaranth densities of 1 and 10 plants per 9.1 m of row reduced cotton yield 13 and 54%, respectively (Morgan et al., 2001). In Oklahoma, 8 Palmer amaranth per 10 m of row reduced cotton yields 53 to 88% (Rowland et al., 1999).

There was no effect of Palmer amaranth density on cotton yield when Palmer amaranth was transplanted at the 12- and 17-leaf stages of cotton and competed with the crop for 94 to 102 days and 80 to 92 days, respectively (Figure 1). Similar findings of reduced competitiveness of late emerging Palmer amaranth populations have been reported with other crops. Palmer amaranth (8 plants m⁻¹ row, 76 cm row spacing) that emerged with the crop and competed for the entire season reduced yields 79 and 91% for soybean and corn, respectively (Bensch et al., 2003; Massinga et al., 2001). When Palmer amaranth emerged 19 to 38 d after soybean planting, there were no detectable effects of weed density on crop yield loss (Bensch et al., 2003). Palmer amaranth that emerged at the 6- to 7-leaf stage of corn reduced corn yields 47% at the highest density (Massinga et al., 2001).
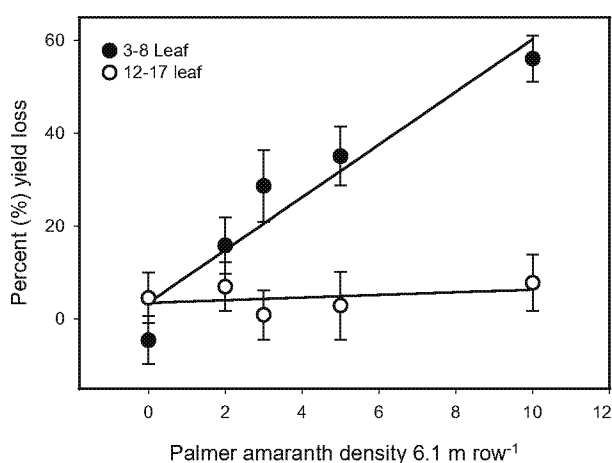

Figure 1. Cotton lint yield in response to cotton leaf stage at time of Palmer amaranth transplanting and Palmer amaranth density. Contrast analyses indicated that significant differences existed between the early (3-8 leaf) and late (12-17 leaf) stages. 3-8 Leaf: Y=3.5+5.7X; p<0.05, R^2=0.38. 12-17 Leaf: NS

In the current study, cotton yield loss estimates do not include potential losses related to harvest interference, as the Palmer amaranth plants were removed prior to picking. Previous research determined that Palmer amaranth reduced cotton harvest efficiency 2- to 4-fold, relative to weed-free controls (Smith et al., 2000). Although Palmer amaranth will reduce cotton yield quantity, previous research has shown that cotton fiber quality parameters were unaffected by the presence of Palmer amaranth (Rowland et al., 1999; Smith et al., 2000).

Palmer amaranth biomass. Palmer amaranth plant biomass was influenced by both cotton leaf-stage at the time of Palmer amaranth transplant and Palmer amaranth density, but not the interaction between these variables. Palmer amaranth plant biomass was greatest (9,190 kg ha⁻¹) when Palmer amaranth was transplanted into treatments with small cotton plants (3- and 8-leaf cotton stages), and 73% lower (2,520 kg ha⁻¹) when transplanted into plots with larger cotton plants (12- and 17-leaf cotton stages). The reduced Palmer amaranth plant biomass at the two later cotton growth stages reflects the greater competiveness of cotton compared to the earlier transplant dates when cotton was smaller, and supports the differences in cotton yield loss among these treatments (Figure 1).

A review of the literature concluded that Palmer amaranth growing in cotton produced greater biomass than 25 other weed species (Askew and Wilcut, 2002). Weed species that produced high amounts of plant biomass in cotton interference studies included tumble pigweed (*Amaranthus albus* L.) (4,000 kg ha⁻¹), jimsonweed (*Datura stramonium* L.) (4,600 kg ha⁻¹), spurred anoda (*Anoda cristata* (L.) Schlecht.) (7,800 kg ha⁻¹), and ladysthumb (*Polygonum persicaria* L.) (8,940 kg ha⁻¹), though all of these studies had weed densities two- to five-fold greater than the densities used in the current study (Askew and Wilcut, 2002; Molin et al., 2006; Rushing et al., 1985; Scott et al., 2000).

Palmer amaranth biomass at the conclusion of the growing season increased in a linear manner with Palmer amaranth plant density per plot (Figure 2). Palmer amaranth plant biomass increased 1,056 kg ha⁻¹ with each Palmer amaranth plant added between 2 and 10 plants per 6.1 m of crop row. The linear response is significant because it may demonstrate a lack of intraspecific interference among Palmer amaranth as density increased, for the range of densities studied. A previous study found intraspecific

interference with Palmer amaranth in cotton at lower densities (0.8 plants m^{-1}) than in the current study (1.6 plants m^{-1} of row) (Rowland et al., 1999). In grain sorghum, there was no intraspecific interference in Palmer amaranth with the maximum density of 1.2 Palmer amaranth plants m^{-1} of row (Moore et al., 2004). While early season population densities of Palmer amaranth in research plots and growers' fields can exceed 50 plants m^{-2} (with heavily infested plots approaching 500 Palmer amaranth seedings m^{-2}), densities at the end of the season are typically <15 Palmer amaranth plants m^{-2} (Personal Observation, T. M. Webster). Whether this apparent self-thinning phenomenon is related to intraspecific interference is not known, but further understanding of this process could benefit weed management.
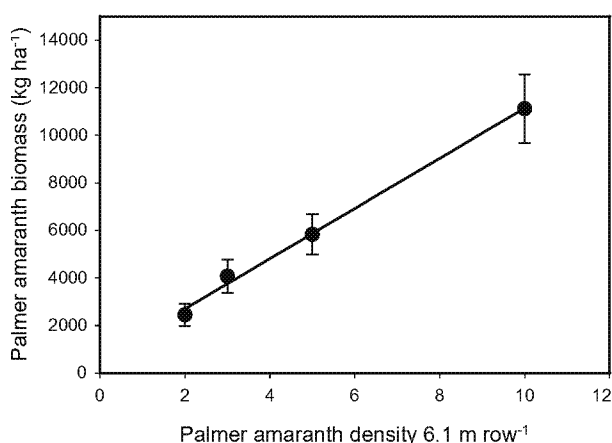

Figure 2. Palmer amaranth biomass as affected by Palmer amaranth density. Data points are averaged over cotton leaf stage at the time of palmer amaranth transplanting. Y=585.9+1055.9X; p<0.05, R^2=0.28

Palmer amaranth seed production. Timing of Palmer amaranth transplanting significantly affected Palmer amaranth seed production; Palmer amaranth density and the interaction between timing and density were not significant. When Palmer amaranth was established at the 3-leaf cotton stage, approximately 61,000 viable seeds per plant were produced, which is equivalent to 1.1 billion seed ha^{-1} at the highest Palmer amaranth density evaluated in this study (1.8 Palmer amaranth plants m^{-2}). Palmer amaranth interfering with peanut in North Carolina produced 1.2 billion seed ha^{-1} at Palmer amaranth density of 5.7 plants m^{-2} (Burke et al., 2007). In Kansas, Palmer amaranth (8 plants m^{-1} row) produced 32,300 seed m^{-2} (323 million seed ha^{-1}) in soybean (Bensch et al., 2003) and 514,000 seeds m^{-2} (5.1 billion seed ha^{-1}) in corn (Massinga et al., 2001). In the current

study, seed production by Palmer amaranth plants transplanted at the 17-leaf stage of cotton was reduced 77% relative to Palmer amaranth plants transplanted at the 3-leaf stage of cotton, but production was still approximately 14,000 seeds per plant. As transplant time during the season was delayed, it was likely that the larger cotton plants were more competitive than Palmer amaranth for limited resources (e.g. water, light, nutrients). However, a previous study determined that Palmer amaranth flowering was hastened by short day length, which diverted resources from vegetative growth, as evidenced through reduced plant height and biomass accumulation, in favor of inflorescence production (Keeley et al., 1987). Similar to the current study, Palmer amaranth that emerged in 6- to 7-leaf stage corn had 83% lower seed production relative to Palmer amaranth that emerged with corn (Massinga et al., 2001). Palmer amaranth (susceptible to glyphosate) that established in South Carolina with soybean in narrow rows spaced 19 cm apart produced 34% fewer seed than those plants growing in soybean rows spaced 91 cm apart (Jha et al., 2008). When growing in the absence of competition, Palmer amaranth planted at monthly intervals in California between March and October had maximum seed production (613,000 seeds $plant^{-1}$) from the May 1 planting (Keeley et al., 1987). Relative to the May 1 planting, seed production per plant was reduced 60 and 86% from Palmer amaranth planted June 1 and July 1, respectively (Keeley et al., 1987). In the current study, there were no differences in Palmer amaranth seed viability at the conclusion of the growing season among Palmer amaranth establishment times or densities (data not shown).

CONCLUSION

The results of this study demonstrate that GR-Palmer amaranth plants that escape early management efforts can significantly reduce cotton yields and produce prodigious amounts of viable offspring (1.1 billion seed ha^{-1}). The lack of irrigation in this on-farm trial necessitated the use of Palmer amaranth transplants from an area of the field adjacent to the test to ensure proper densities and appropriate Palmer amaranth emergence timings. While this methodology tried to approximate late-emerging Palmer amaranth plants, it is possible that crop yield losses were either over- or under-estimated. However, there were similarities to previous studies in: 1) Palmer amaranth seed production (Burke et

al., 2007), 2) cotton yield losses from early-season transplanted populations in this study and full-season interference in other studies (Morgan et al., 2001; Rowland et al., 1999), and 3) reduced yield loss from late-transplanted treatments in this study and late-emerging Palmer amaranth plants in other crops (Bensch et al., 2003; Massinga et al., 2001).

A survey of cotton growers revealed that prior to the occurrence of GR-Palmer amaranth in GA, less than 26% of the cotton land was treated with herbicides that have soil residual activity. A similar area was treated with two or more residual herbicides at planting once GR-Palmer amaranth became prevalent (Culpepper et al., 2010). The effectiveness of these herbicides is dependent upon a number of factors, including: proper activation through rainfall/ irrigation, lack of herbicide-interception and binding by mulch residues (Potter et al., 2008; Potter et al., 2011), and appropriate timing of herbicide activation relative to weed germination. Herbicides with soil residual activity often begin to fail prior to cotton canopy closure, allowing Palmer amaranth to emerge, compete with cotton for resources, and interfere with cotton growth and yield. Based on the current study, Palmer amaranth that emerges before the 12-leaf stage of cotton is likely to cause the most cotton yield loss. However, Palmer amaranth that emerges at the 17-leaf stage of cotton, simulating an escape from a layby application could produce sufficient seed to replenish the soil seedbank.

ACKNOWLEDGEMENTS

REFERENCES

Askew, S.D., and J.W. Wilcut. 2002. Ladysthumb interference and seed production in cotton. Weed Sci. 50:326-332.

Bensch, C.N., M.J. Horak, and D. Peterson. 2003. Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci. 51:37-43.

Burke, I.C., M. Schroeder, W.E. Thomas, and J.W. Wilcut. 2007. Palmer amaranth interference and seed production in peanut. Weed Technol. 21:367-371.

Culpepper, A.S., T.L. Grey, W.K. Vencill, J.M. Kichler, T.M. Webster, S.M. Brown, A.C. York, J.W. Davis, and W.W. Hanna. 2006. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci. 54:620-626.

Culpepper, A.S., and J.M. Kichler. 2009. University of Georgia herbicide programs for controlling glyphosate-resistant Palmer amaranth in 2009 cotton. University of Georgia Collge of Agricultural and Environmental Sciences, Circ. No. 924 (http://mulch.cropsoil.uga.edu/weedsci/HomepageFiles/Palmer2009.pdf) Accessed 28 May 2009.

Culpepper, A.S., T.M. Webster, L.M. Sosnoskie, and A.C. York. 2010. Glyphosate-resistant Palmer amaranth in the US. *In*: Nandula VK, editor. Glyphosate Resistance: Evolution, Mechanisms, and Management. Hoboken, NJ: John Wiley & Sons, Inc. Pp 195-212.

Culpepper, A.S., J.R. Whitaker, A.W. MacRae, and A.C. York. 2008. Distribution of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in Georgia and North Carolina during 2005 and 2006. J. Cot. Sci. 12:306-310.

Ehleringer, J. 1983. Ecophysiology of *Amaranthus palmeri*, a Sonoran Desert summer annual. Oecologia 57:107-112.

Fast, B.J., S.W. Murdock, R.L. Farris, J.B. Willis, and D.S. Murray. 2009. Critical timing of Palmer amaranth (*Amaranthus palmeri*) removal in second-generation glyphosate-resistant cotton. J. Cot. Sci. 13:32-36.

Gaines, T.A., W. Zhang, D. Wang, B. Bukun, S.T. Chisholm, D.L. Shaner, S.J. Nissen, W.L. Patzoldt, P.J. Tranel, A.S. Culpepper, T.L. Grey, T.M. Webster, W.K. Vencill, R.D. Sammons, J. Jiang, C. Preston, J.E. Leach, and P. Westra. 2010. Gene amplification confers glyphosate resistance in *Amaranthus palmeri*. Proc. Natl. Acad. Sci. U. S. A. 107:1029-1034.

Gibson, A.C. 1998. Photosynthetic organs of desert plants. Bioscience 48:911-920.

Guo, P.G., and K. Al-Khatib. 2003. Temperature effects on germination and growth of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*). Weed Sci. 51:869-875.

Heap, I.M. 2012. International Survey of Herbicide Resistant Weeds (http://www.weedscience.org/in.asp), Last accessed 19 October 2012.

Horak, M.J., and T.M. Loughin. 2000. Growth analysis of four *Amaranthus* species. Weed Sci. 48:347-355.

Jha, P., J.K. Norsworthy, W. Bridges, and M.B. Riley. 2008. Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci. 56:408-415.

Keeley, P.E., C.H. Carter, and R.J. Thullen. 1987. Influence of planting date on growth of Palmer amaranth (*Amaranthus palmeri*). Weed Sci. 35:199-204.

Massinga, R.A., R.S. Currie, M.J. Horak, and J. Boyer. 2001. Interference of Palmer amaranth in corn. Weed Sci. 49:202-208.

Molin, W.T., D. Boykin, J.A. Hugie, H.H. Ratnayaka, and T.M. Sterling. 2006. Spurred anoda (*Anoda cristata*) interference in wide row and ultra narrow row cotton. Weed Sci. 54:651-657.

Moore, J.W., D.S. Murray, and R.B. Westerman. 2004. Palmer amaranth (*Amaranthus palmeri*) effects on the harvest and yield of grain sorghum (*Sorghum bicolor*). Weed Technol. 18:23-29.

Morgan, G.D., P.A. Baumann, and J.M. Chandler. 2001. Competitive impact of Palmer amaranth (*Amaranthus palmeri*) on cotton (*Gossypium hirsutum*) development and yield. Weed Technol. 15:408-412.

Nichols, R.L., J. Bond, A.S. Culpepper, D. Dodds, V. Nandula, C.L. Main, M.W. Marshall, T.C. Mueller, J.K. Norsworthy, A. Price, M. Patterson, R.C. Scott, K.L. Smith, L.E. Steckel, D. Stephenson, D. Wright, and A.C. York. 2009. Glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) spreads in the Southern U.S. Resistant Pest Management Newsletter 18:8-10.

Place, G., D. Bowman, M. Burton, and T. Rutty. 2008. Root penetration through a high bulk density soil layer: differential response of a crop and weed species. Plant Soil 307:179-190 (DOI: 10.1007/s11104-008-9594-4).

Potter, T.L., C.C. Truman, T.C. Strickland, D.D. Bosch, and T.M. Webster. 2008. Herbicide incorporation by irrigation and tillage impact on runoff loss. J. Environ. Qual. 37:839-847.

Potter, T.L., C.C. Truman, T.M. Webster, D.D. Bosch, and T.C. Strickland. 2011. Tillage, cover-crop residue managment, and irrigation incorporation impact on fomesafen runoff. J. Agric. Food Chem 59:7910-7915.

Rowland, M. W., D.S. Murray, and L.M. Verhalen. 1999. Full-season Palmer amaranth (*Amaranthus palmeri*) interference with cotton (*Gossypium hirsutum*). Weed Sci. 47:305-309.

Rushing, D.W., D.S. Murray, and L.M. Verhalen. 1985. Weed interference with cotton (*Gossypium hirsutum*). II. Tumble pigweed (*Amaranthus albus*). Weed Sci. 33:815-818.

SAS. 2003. SAS Procedures Guide. Version 9.1. Cary, NC. SAS Institute.

Scott, G.H., S.D. Askew, J.W. Wilcut, and C. Brownie. 2000. *Datura stramonium* interference and seed rain in *Gossypium hirsutum*. Weed Sci. 48:613-617.

Smith, D.T., R.V. Baker, and G.L. Steele. 2000. Palmer amaranth (*Amaranthus palmeri*) impacts on yield, harvesting, and ginning in dryland cotton (*Gossypium hirsutum*). Weed Technol. 14:122-126.

Sosnoskie, L.M., T.M. Webster, A.W. MacRae, T.L. Grey, and A.S. Culpepper. 2012. Pollen-mediated dispersal of glyphosate-resistance in Palmer amaranth under field conditions. Weed Sci. 60:366-373.

Steckel, L.E. 2007. The dioecious *Amaranthus* spp.: Here to stay. Weed Technol. 21:567-570.

Steckel, L.E., C.L. Main, A.T. Ellis, and T.C. Mueller. 2008. Palmer amaranth (*Amaranthus palmeri*) in Tennessee has low level glyphosate resistance. Weed Technol. 22:119-123.

Steckel, L.E., C.L. Sprague, E.W. Stoller, and L.M. Wax. 2004. Temperature effects on germination of nine *Amaranthus* species. Weed Sci. 52:217-221.

Wright, S.R., M.W. Jennette, H.D. Coble, and T.W. Rufty. 1999. Root morphology of young *Glycine max*, *Senna obtusifolia*, and *Amaranthus palmeri*. Weed Sci. 47:706-711.